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# Thermophilic digestion of waste-activated sludge coupled with solar pond

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ABSTRACT

Thermophilic anaerobic digestion (AD) is an efficient treatment process for waste activated sludge with enhanced hydrolysis and digestion rates. However, the costs associated with maintaining high temperature for thermophilic digester should be minimized and the thermal stability of the reactor should be maximized for its practical use. This study tested an integrated system consisting of a solar pond and an AD reactor for digestion of waste activated sludge. The integrated system could be stably operated at 51.6 ± 1.5 °C in sunny days (and nights) and maintained digestion performance over at least three days with cloud and rain. On the contrary, the control reactor without solar pond experienced significant temperature fluctuation and poor digestion performance. After 29d, the integrated system thermophilic reactor removed 65.0 ± 4.2% of total chemical oxygen demands and produced 79% excess biogas. The concentrations of soluble chemical oxygen demand, protein and saccharides in digester with solar pond were higher than those in that without the pond. Also, the presence of solar pond enhanced hydrolysis and degradation of soluble microbial byproduct-like compounds with carboxylic groups and amide-2 groups in sludge.



## 1. Introduction

Sewage sludge is a by-product of wastewater treatment processes, which is rich in organic carbons, pathogens, and many other environmental pollutants [1]. The sludge must be stabilized before its final disposal or utilization [2]. Anaerobic digestion (AD) has been practiced for one than a century, and is still one of the most common processes for sludge stabilization [3]. Biogas was produced as an end product for the AD process, which can be used as a renewable energy recovered from waste [4]. However, a main drawback of AD is its slow biological degradation rate, which results in long digestion time and large digester volumes [5–20]. Recent developments on high-solid AD are noticeable for supporting high organic loading rate systems [21–24].

Thermophilic AD operating at 45–60 °C was proposed to enhance hydrolysis and digestion rates of the feed substrate under environmental environment [25–28]. Nges and Liu [29] confirmed that higher biogas production from anaerobic digestion of sewage sludge using continuous stirred tank reactors could be enhanced at 50 °C compared with that at 37 °C. Numerous studies confirmed that the thermophilic AD can produce additional biogas and improved hygiene residue with maximum sludge volume reduction [30–32]. Cavinato et al. [33] demonstrated that the shift of reaction temperature from 37 °C to 55 °C increased the specific biogas production from 0.34 to 0.49 $m^3$/kg total volatile solids (TVS) and the gas production rate from 0.53 to 0.78 $m^3$ per $m^3$ of reactor per day. Ge et al. [34] reported that the degradability of their sludge was increased from 21% to 49% when temperature was increased from 50 to 65 °C. Ho et al. [35] employed stable isotopic signatures ($\delta^{13}C$) to reveal that elevated temperature promoted syntrophic acetate oxidation on methane production. Although thermophilic AD had advantages over mesophilic AD, the costs associated with maintaining high temperature for the former may offset the benefits of its high reaction rates [4]. Additionally, mesophilic AD also experiences large temperature fluctuations in response to the change in surrounding temperatures, which led to unstable performance and frequent breakdowns of the reactors [36]. Thus, finding a low cost

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heat source associated with the thermophilic AD is of practical interest [37].

A salt gradient solar pond (SGSP) is pool of saline water that effectively collects and stores incipient solar radiation with large thermal capacitance [38]. Under normal operation condition, pool temperatures higher than 80 °C were noted [39,40]; in some cases pool temperatures as high as 110 °C were reported in an outdoor solar pond [41]. To our best knowledge, there is no study available on the performance of an integrated SGSP+thermophilic AD system. This study tested the feasibility of applying such an integrated system with energy collected from solar pond and with high buffering in reactor temperature.

## 2. Materials and methods

### 2.1. Reactors

The tested lab-scale SGSP+AD (R1) consisted of a solar pond with quadrangular frustum (upper surface of 150 cm × 150 cm, bottom surface of 40 cm × 40 cm, and height 50 cm) and an anaerobic digester in cylindrical shape (diameter 28 cm, height 25 cm, work volume of 15 L), with the latter being embedded in the lower convective zone (LCZ) of the former (see Fig. 1). Measurements showed that the solar pond contained tree layers: upper convective zone (UCZ, nearly fresh water) of 8 cm thick, non-convective zone (NCZ, 15% w/w NaCl) of 12 cm thick, and LCZ (25% w/w NaCl) of 30 cm thick. The outer surface of solar pond was insulated to reduce external heat loss. The whole setup was placed in a soil ground in Shanxi University (Taiyuan, China; 37°48′2.84″N 112°35′10.36″E), with its top 5 cm portion above the soil surface. The average radiation intensity in the testing period (2014 July–August) was 18.2 MJ $m^{-2}$ $d^{-1}$.

Another identical setup was placed just beside R1 but without the solar pond. This reactor is named R2 as a control.

### 2.2. Operational conditions

Sludge samples (feed) were collected from the secondary sedimentation tank in a municipal wastewater treatment plant of Taiyuan (China) and were stored at 4 °C after sampling. The feed sludge had the following properties: pH 6.73, volatile solids concentration (VS) of 16000–18000 mg $L^{-1}$, total solids concentration (TS) of 18500–21000 mg $L^{-1}$, total chemical oxygen demand (TCOD) of 24000–28000 mg $L^{-1}$ and soluble chemical oxygen demand (SCOD) of 960–1290 mg $L^{-1}$, water content of 97–98%, and ammonia-nitrogen ($NH_4^+$-N) of 120–180 mg $L^{-1}$.

The tests were conducted in batch mode. At startup, both R1 and R2 were filled with 100:1 (v/v) mix of raw sludge and effluent from another mesophilic mature sludge anaerobic digester. The high mix ratio adopted herein is to minimize the growth rate of mesophilic strains in the mesophilic inoculum for R2. The mixers stirred the suspension of R1 and R2 at 80 rpm. The reactor temperatures were monitored using a real-time monitoring recorder (KT500, Hangzhou Pangu Automation System Co., Ltd, Huangzhou, China).

### 2.3. Analytical methods

#### 2.3.1. Extraction and fractionation of extracellular biological organic matter (EBOM)

The EBOM of sludge was defined as the organic compounds strongly attached on the solid particles that could only be released by extraction [42]. The organic matters presented in supernatant liquid were regarded as supernatant organics. The EBOM of the raw sludge and digested sludge was extracted followed the procedures by Chen et al. [43]. In brief, the sludge samples were centrifuged (6000 × g) for 20 min, with the supernatant being collected. 100 g of the so-yielded solid residue was slowly mixed with 200 ml of 25% (v/v) $NH_4OH$ for 24 h, and then filtered with 0.45 μm cellulose nitrate membrane filter.

#### 2.3.2. Spectra analysis

The excitation–emission matrix (EEM) was applied for characterizing the fluorescence properties of the sludge samples. The samples were diluted with 0.01 M KCl solutions to 1 mg $L^{-1}$ dissolved organic carbon (DOC) and acidified to pH 3 with concentrated HCl. A spectrofluorometer (FP-6500 Jasco, Tokyo, Japan) with axenon lamp was applied to collected EEM spectra of samples at 25 °C. Each EEM lot was generated by scanning excitation wavelengths from 220 to 400 nm with 5 nm steps and emitting fluorescence between 280 and 480 nm with 1 nm steps.

The infrared spectra of samples were obtained using 2 mg of dried powders lyophilized in potassium bromide pellets. The Perkine Elmer Spectrum One B Fourier Transform Infrared (FTIR) spectrometer (Waltham, Massachusetts, USA) was scanned from 4000 $cm^{-1}$ to 400 $cm^{-1}$. The spectra were baseline corrected and normalized to 1.0 for comparison.

#### 2.3.3. Chemical analysis

Concentrations of total chemical oxygen demand (TCOD), TS, soluble chemical oxygen demand (SCOD), and $NH_4^+$-N, pH of sludge

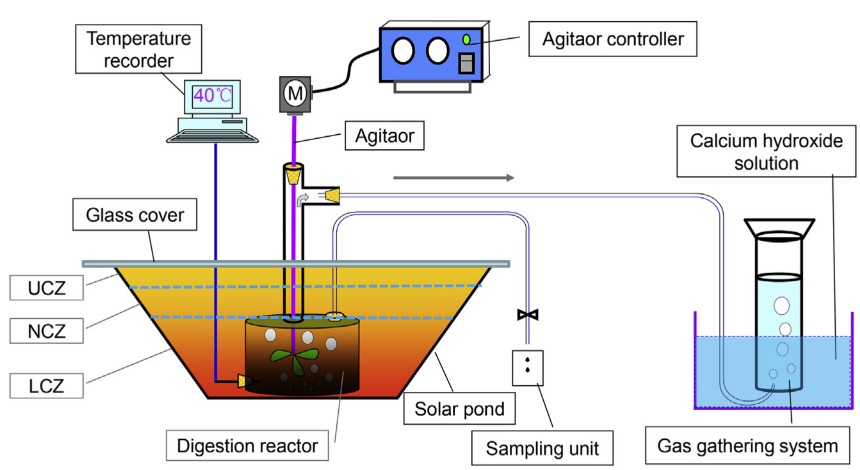


**Fig. 1.** Schematics of the reactor SGSP+AD (R1). UCZ: upper convective zone (8 cm); NCZ: non-convective zone (12 cm); LCZ: lower convective zone (30 cm).